# MODELING OF GYPSUM DISSOLUTION DRIVEN BY VARIABLE DENSITY FLOW IN THE COASTAL KARST AQUIFER OF LESINA MARINA (SOUTHERN ITALY)

**Maria D. Fidelibus**[1], Claudia Campana[2]
[1] DICATECh, Politecnico di Bari, Bari, BA, Italy
[2] Autorità di Bacino della Puglia, Valenzano, BA, Italy

## ABSTRACT

The application of a combined *reactive transport - density dependent flow model* to a real gypsum coastal aquifer (Lesina Marina, Southern Italy) is presented, with the aim of evaluating the potential of gypsum dissolution on sinkholes development. The area has been in fact highly susceptible to hazardous and rapid sinkhole formation since 1927, when a canal was excavated in an evaporite formation, strongly modifying groundwater flow patterns. To achieve this aim, firstly a conceptual model is defined, then a density-dependent, tide-influenced, flow model is set up and solved by means of the numerical code SEAWAT. Finally, the resulting transient flow field is used by the reactive multicomponent transport model PHT3D to estimate gypsum dissolution rate. The multi-disciplinary approach indicates that sinkhole formation in the Lesina Marina area, during the last 90 years, is scarcely connected to recent gypsum dissolution; rather, it is related to the erosion of paleo-cavities filling material (*suffosion*), caused by the new hydrodynamic conditions induced by the excavation of the canal within the evaporite formation.

## INTRODUCTION

Evaporites are the most soluble rocks, which dissolve to form karst features such as those typically found in limestones, though in a shorter time. Even if the studies of Sanford and Konikow (1989) and Rezaei et al. (2005) focus on hypothetical and simplified conditions, they provide important insights into dissolution processes in carbonate coastal aquifers by using a combined geochemical-hydrodynamic modeling approach.

This study deals with the first application of a reactive transport model coupled with a variable-density groundwater flow model to a coastal gypsum aquifer, with the purpose of ascertaining time evolution of sinkholes. Numerous geochemical and hydrological data were collected both to build and validate the model. The study-site, the Lesina Marina residential area (Puglia, Southern Italy; Figure 1) is located between a lagoon and the seacoast. The Acquarotta Canal connects the Lesina lagoon to the sea: it was excavated in 1927 in an evaporite formation, changing groundwater flow patterns in the area. Since the canal was excavated, sinkholes have developed exponentially over time.

## FIELD DATA INTERPRETATION

The conceptual model for the Lesina Marina study area (about 1 $km^2$) is based on field studies carried out between 2008 and 2012 and on previous studies (Fidelibus et al., 2011). Of the 131 drillings with core recovery for stratigraphic and petrographic aims, 41 were equipped as monitoring wells for groundwater hydraulic head measure (Figure 1) and sampling. A geochemical survey along a transect (Figure 1) was completed in 2012.

Based on information from cores, the lithological succession was simplified defining only two main hydro-stratigraphic units: a sandy cover and the evaporite bedrock. Groundwater level monitoring data provide evidence that the main flow direction is towards a few breaks realized for environmental reasons in the '90s during maintenance works on the left bank cover of the canal. Indeed, the excavation of the Acquarotta Canal in the evaporite bedrock caused changes in the original groundwater flow rate and direction: the canal, working as a drain, induced an amplification of the groundwater level oscillation due to sea tide. Finally, the hydrochemical study led to evidence that gypsum dissolution is an active process influenced by concurrent processes, and that freshwater-seawater mixing enhances gypsum dissolution, moreover inducing ion-exchange, whose direction is influenced by hydrodynamic conditions.

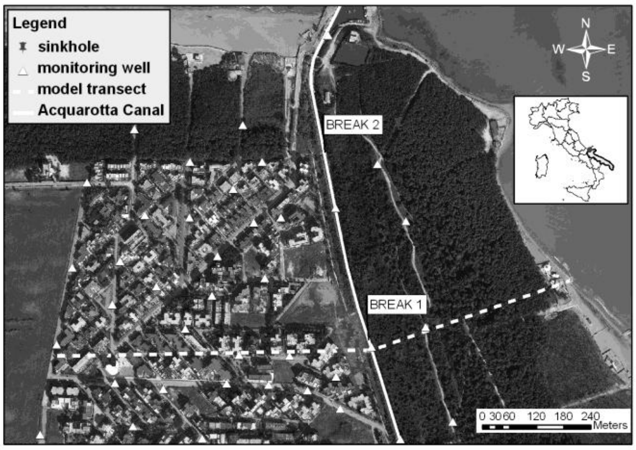


**Figure 1: Lesina Marina study area: sinkholes (last updated in March 2012) and monitoring wells locations; white dashed line shows the model transect**

## MODEL DEVELOPMENT

### *Assumptions of the conceptual model*

The relevant domain chosen to represent the study-area is a 2D vertical transect (Figure 1), corresponding to a main flowline. Within the model transect there are an internal boundary (Acquarotta Canal, controlling the aquifer hydrodynamic regime with its level oscillations), and two external boundaries, landward and seaward. Both the two selected hydro-stratigraphic units can be modeled implementing the equivalent continuum model, since for the chaotic evaporite bedrock in particular, a discrete fracture network model does not seem practical: the complexity of the system "drowns" local variations so that a whole description is impossible. In coupling hydro-geochemistry and transport driven by groundwater flow, we assumed local equilibrium conditions (LEA) and isotherm conditions. As a consequence, viscosity and density dependence on temperature can be neglected. Therefore, the density equation of state assumes the form of the empirical relation developed by Baxter and Wallace (1916).

### *Simulation codes, temporal and spatial discretization, initial and boundary conditions, hydrogeological properties*

The modeling consisted of three phases. During the first phase the aquifer was assumed to be initially filled with fresh groundwater: subsequently, a 200-yr transient simulation using SEAWAT Version 4 (Langevin et al., 2008) followed in order to define saltwater and freshwater equilibrium as initial conditions for the following phase. The second modeling phase encompasses high temporal resolution to simulate the effects of tidal fluctuations and their propagation through the aquifer for 356 days and 19 hours. Dirichlet boundary conditions were also used for this second phase; however, the prescribed values changed in time based on observed data (hourly data for the 2010-2011 period). The transient flow field resulting from SEAWAT simulation was used as advective input for the third modeling phase of reactive transport. For this simulation, the chemical composition of groundwater and the mineral composition of the aquifer rocks were added as initial information; following this, chemical reactions, together with transport of aqueous species, were implemented by PHT3D code (Prommer et al., 2003) that couples the transport simulator MT3DMS and the geochemical modeling code PHREEQC-2.

The two-dimensional model grid consists of 332 columns (widths from 4 to 1 m) and 23 layers, each 1.29 m thick, except for the top layer: the bottom of layer 1 is set lower than the minimum expected groundwater level to avoid wetting and drying complications in the model. A type of "zone continuum model" (Langevin, 2003) was developed to define hydrogeological properties. Five discrete zones of different permeability were identified within the gypsum layer on the basis of the core data; their properties were calibrated on observed data. With the aim of introducing tidal boundary conditions, the surface water bodies (canal and sea) within the transect were explicitly simulated by using the "high-K approach" (Mulligan et al., 2011).

## RESULTS

Results from the simulation steps are compared with experimental data collected at observation wells located within the model domain. For the tide-influenced model, simulated groundwater level fluctuations in observation wells were compared to monitoring data for the entire simulation period (about 1 y): observed and modeled data are in good agreement. The observed TDS concentration distribution is also satisfactorily reproduced by the model. The reactive transport model outcomes are the distributions of chemical species within the model domain, resulting from simulated water-rock interactions. For solid phases, i.e. minerals composing the geological formations, the results after the 1-y simulation of tidal effects on the coastal aquifer are interesting in terms of concentration variations between initial equilibrated and final conditions. Because of LEA and its inconsistency with precipitation kinetics, model results for the most permeable zone close to the canal should be considered highly uncertain and underrated. Apart from this zone, model results for gypsum seem to characterize the expected processes: negative deltas (gypsum dissolution) correspond to the freshwater-saltwater transition zone, towards the freshwater side.

## DISCUSSION AND CONCLUSIONS

We can express the simulated gypsum dissolution rate in terms of porosity change in the adopted time unit (years). The porosity change rates within the model domain (Figure 2) suggest that the dominant evolution time of gypsum dissolution is much greater than a human lifetime. The zones where the rate is higher correspond to the transition zone: this explains the presence of paleo-cavities within the evaporite formation, linked also to eustatic sea level changes. For the convective canal surroundings, the model gives the highest rate of porosity development, together with highly underestimated values (due to gypsum precipitation).

Hence, the model results indicate that sinkhole development in the Lesina Marina area is scarcely connected to recent gypsum dissolution. Rather, it is related to *suffosion* (erosion of paleo-cavities filling material) due to changes in hydrodynamic conditions induced by the canal. On the contrary, modeling results indicate the canal surroundings as the most critical zone for gypsum dissolution: however, there the model does not reproduce real geochemical behavior as a whole, since chemical kinetics and feedback processes are not simulated.

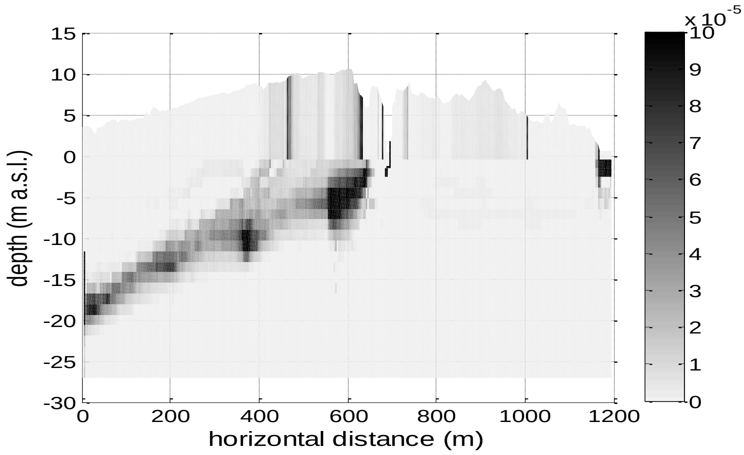


**Figure 2: Porosity change in 1 year within the model transect**

## CITED REFERENCES

Baxter G.P. and C.C. Wallace. 1916. Changes in volume upon solution in water of halogen salts of alkali metals. II. American Chemical Society Journal 38: 70-104.

Fidelibus M.D., F. Gutierrez, and G. Spilotro. 2011. Human-induced hydrogeological changes and sinkholes in the coastal gypsum karst of Lesina Marina area (Foggia Province, Italy). Engineering Geology 118:1-19.

Langevin C.D. 2003. Stochastic Ground Water Flow Simulation with a Fracture Zone Continuum Model. Ground Water, Vol.41, No. 5: 587–601.

Langevin C.D., D. Thorne, A.M. Dausman, M.C. Sukop, and W. Guo. 2008. SEAWAT Version 4: A Computer Program for Simulation of Multi-Species Solute and Heat Transport. U.S. Geological Survey Techniques and Methods, Book 6, Chapter A22.

Mulligan A.E., C.D. Langevin, and V.E.A. Post. 2011. Tidal Boundary Conditions in SEAWAT. Ground Water, Vol. 49, No. 6: 866–879.

Prommer H., D.A. Barry, and C. Zheng. 2003. MODFLOW/MT3DMS-Based Reactive Multicomponent Transport Modeling. Ground Water, Vol. 41, No. 2: 1-11.

Rezaei M., E. Sanz, E. Raeisi, C. Ayora, E. Vázquez-Suñé, and J. Carrera. 2005. Reactive transport modeling of calcite dissolution in the fresh-salt water mixing zone. Journal of Hydrology 311: 282–298.

Sanford W.E. and L.F. Konikow. 1989. Simulation of calcite dissolution and porosity changes in saltwater mixing zones in coastal aquifers. Water Resources Research 25: 655–667.

**Contact Information**: Claudia Campana, Autorità di Bacino della Puglia, Str. Prov. per Casamassima, Km 3 - 70010 Valenzano, BA, Italy, Phone: 0039 080 9182224
Fax: 0039 080 9182244, Email: claudia.campana@adb.puglia.it